

Hubble Space Telescope Servicing Mission Four (HST SM4) EVA Challenges for Safe Execution of STS-125

Robert P. Dedalis⁽¹⁾, William H. Hill⁽²⁾, Karin Bergh Rice⁽³⁾, Ann M. Cooter⁽⁴⁾

⁽¹⁾NASA, 8800 Greenbelt Road, Greenbelt, MD 20771, Email: robert.p.dedalis@nasa.gov

⁽²⁾ManTech International Corporation, 7474 Greenway Drive Greenbelt, MD 20770, Email: william.h.hill@nasa.gov

⁽³⁾Lockheed Martin (former), 7400 Greenway Drive Greenbelt, MD 20770, Email: kcbergh@comcast.net

⁽⁴⁾Harris Corporation, 7375 Executive Place, 4th Floor, Seabrook, MD 20706, Email: amcooter@gmail.com

ABSTRACT

In May of 2009, the world-renowned Hubble Space Telescope (HST) received a suite of new instruments and a refurbished bus to enable science for many years to come. The restoration was conducted on-orbit by four spacewalkers on five carefully scripted Extra-Vehicular Activity (EVA) days. Assuring the safety of the spacewalkers and their crewmates required careful attention to tool development, detailed procedures for every activity and many rehearsals with engineers and crew to ensure that everything worked together. Additionally, evolution of EVA requirements since the last servicing mission in 2002, and the broad scope of the mission demanded a much higher degree of safety participation in hardware design and risk acceptance than for previous servicing missions.

1. BACKGROUND

The Hubble Space Telescope (HST) fourth servicing mission (SM4) provided a final upgrade to one of the most productive assets in NASA's collection of science producing instruments currently looking to the stars. HST is unique as it was designed and built to facilitate on-orbit repair and designed for upgrades of critical

spacecraft subsystems and scientific instruments by servicing. Due to servicing, HST has remained operational and productive over the last 17 years since Servicing Mission 1 in 1993. Prior to SM4, and including SM1, there have been four other visits to the telescope (one servicing mission was broken into two parts due to the extent of the repairs and replacements). Due to the imminent retirement of the shuttle, Servicing Mission Four (4) was the final opportunity to restore and enhance the telescope's capabilities using the orbiter. Fig. 1 provides an outline of HST and summarizes the repairs and replacements made for SM4.

STS-125 included a crew of seven for an 11 day mission with 2 contingency days, in case of problems. Of the 7 crew members, 4 were designated spacewalkers. The 4 spacewalkers were divided into 2 teams of 2 with 1 team scheduled for 2 Extra-Vehicular Activity (EVA) days and the second team scheduled for 3 EVA days. Spacewalkers are limited to 3 EVAs during a mission, thus one contingency EVA was reserved for potential shuttle repairs or problems with HST deployment. Each EVA was planned for over 6 hours. During the mission, some approached the limits for acceptable duration.

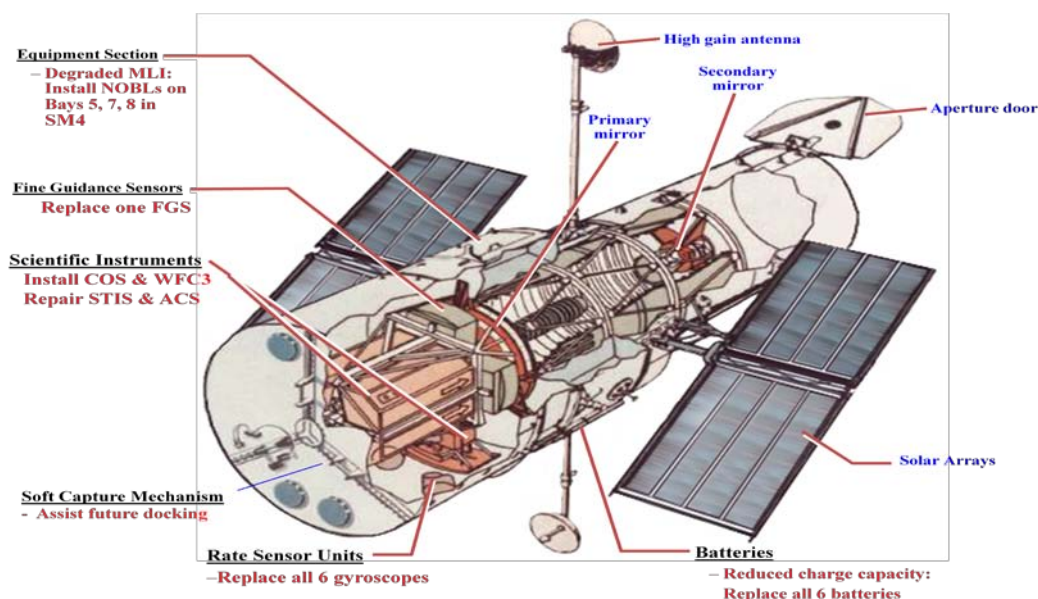


Figure 1. Hubble Space Telescope Replacement Unit

The EVA timeline (Fig. 2) identifies the plan used to replace and or repair HST systems. The timeline was carefully crafted for EVA efficiency to ensure the effective use of every second available for servicing.

The first EVA focused on replacement of Wide Field Camera (WFC) and Scientific Instrument Command and Data Handling module and addition of the Soft Capture Mechanism (SCM) and Latch Over-Center Kits (LOCKS). The second EVA enhanced core HST systems by installing new rate sensor units (RSUs) and

one battery module. EVA 3 tasks include the installation of the Cosmic Origins Spectrograph (COS) and complete repair of the Advanced Camera for Surveys (ACS). EVA 4 time was used to repair the Space Telescope Imaging Spectrograph (STIS). EVA 5 marked the final SM4 EVA with the replacement of the Fine Guidance System, and replacement of the bay 3 battery module.

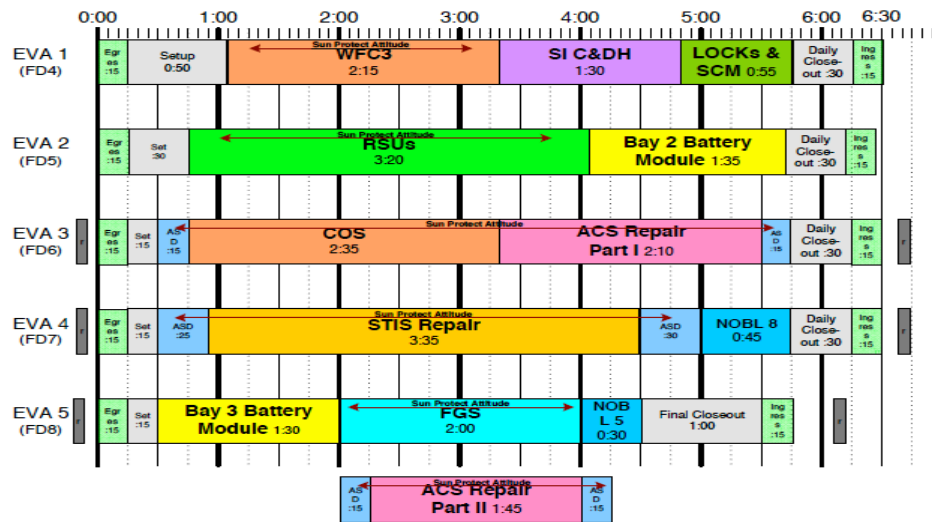


Figure 2. HST SM4 EVA Timeline

2. INTRODUCTION

An integral part of the safety process is the validation of hazard controls implemented by the HST EVA Team with final verification conducted by the HST Safety Team and documented in the Verification Tracking Log (VTL). As with past missions the HST Project developed, validated and verified mission requirements for SM4. Each engineering discipline has a specific set of requirements that must be met. Safety requirements span disciplines, and particularly EVA activities where specific tool development is crucial to the crew's ability access replacement units and instruments in order to perform the tasks within the time limits proscribed within the EVA Timeline.

When the mission was re-established in 2006, the initial effort was to gain an understanding of new or modified requirements based on previous servicing missions which were based on past and near term International Space Station (ISS) EVAs. These new requirements were based on new tools and interfaces developed well

after the HST was designed and the last servicing mission was flown. As HST remains on-orbit and so cannot be retro-fitted, HST was not able to fully comply with the new requirements. Additionally, the hardware used to transport the replacement units and instruments was built during and for previous servicing missions.

The complexity of the repairs on HST required tools with functional sharp edges capable of cutting, prying and clamping. Additionally, the tools had to interface with an orbiting spacecraft deployed in 1990, and equipment built between 1990-2000. Thus, it was not possible to fully meet all of the safety requirements meant for an orbiting platform currently under construction.

Through the Safety and EVA process, safety requirements and operational controls were developed and implemented to address the challenging EVA hazards to keep the crew safe. Fig. 3 illustrates this process.

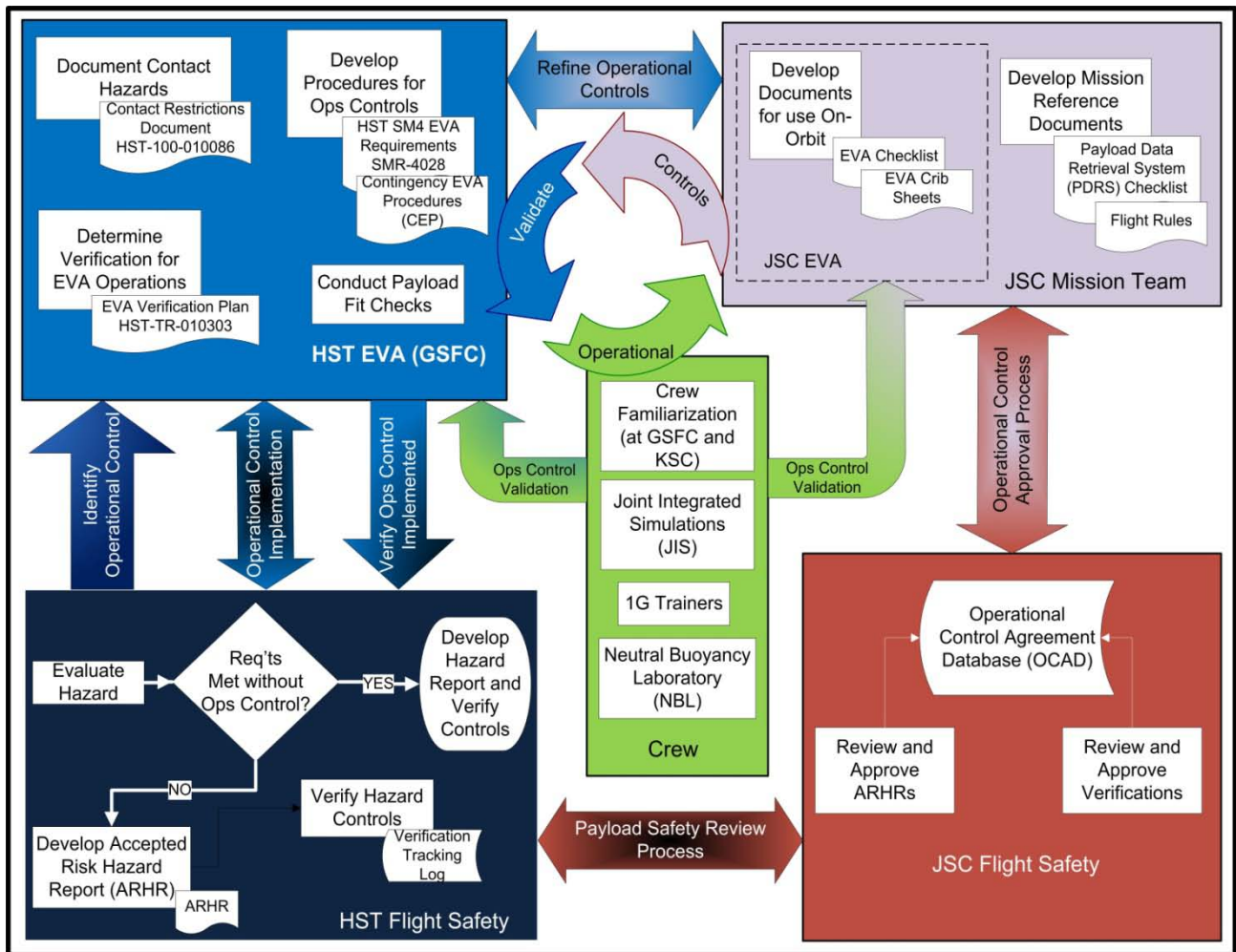


Figure 3. Process for identifying, implementing and approving Operational Controls

3. SAFETY PROCESS

The safety process began with a complete Preliminary Hazard Assessment (PHA). For SM4 this included the systems/sub-systems as well as tools, equipment, crew position, contact hazards and crew activities to determine the overall hazard potential. Hazards identified for similar EVA tasks performed on previous missions were also considered. As in past missions the team followed Johnson Space Center's (JSC) phased safety review process through the JSC Payload Safety Review Panel (PSRP). The phased review process applies to all new Hazard Reports; new carrier hardware and software, new batteries, instruments, mission environments, and EVA operations. Mission safety elements including controls and verifications were briefed to the PSRP for approval.

New to HST's safety team was a new process for safety requirement non-compliances adopted by the PSRP for use on the ISS. Due to the inability to remove non-

conforming interfaces and the need for non-compliant tools, operational controls to protect the crew were necessary. Operational controls are based on the belief that an informed crew, knowledgeable in the location and presence of hazards will take the appropriate cautions to reduce the risk to an acceptable level. To address such hazards that cannot be controlled by physical inhibits or design, JSC's PSRP adopted an Accepted Risk Hazard Report (ARHR) format based on a risk mitigation approach from the United States Air Force. Using this approach, risks are defined by consequence and likelihood. Mitigations through operational controls are defined and tracked through closure using mission documentation for verification. ARHR's replaced the Non-Compliance Reports (NCRs) used to document similar hazards on previous servicing missions. All previous waivers and deviations were rescinded when the mission was reinstated in October 2006. "Grandfathering" was not an option for designs not meeting requirements.

ARHRs captured HST Safety's mitigation approach to many of the unique challenges on SM4. Through the ARHR process, the safety team identified the following risks mitigated through operational controls: kick-loads, contact hazards (sharp edges, touch temperatures), portable foot restraint (PFR) socket loads, and hot connectors. Analysis and inspection identified the hazards, however in most cases, these hazards could

only be controlled by managing EVA processes to implement operational controls. Controls for these hazards were verified by documenting the controls through a "Caution or Warning Statement" in the EVA Requirements Documentation and Contract Restrictions Document. Figure 4 provides an overview of the ARHR's on HST SM4.

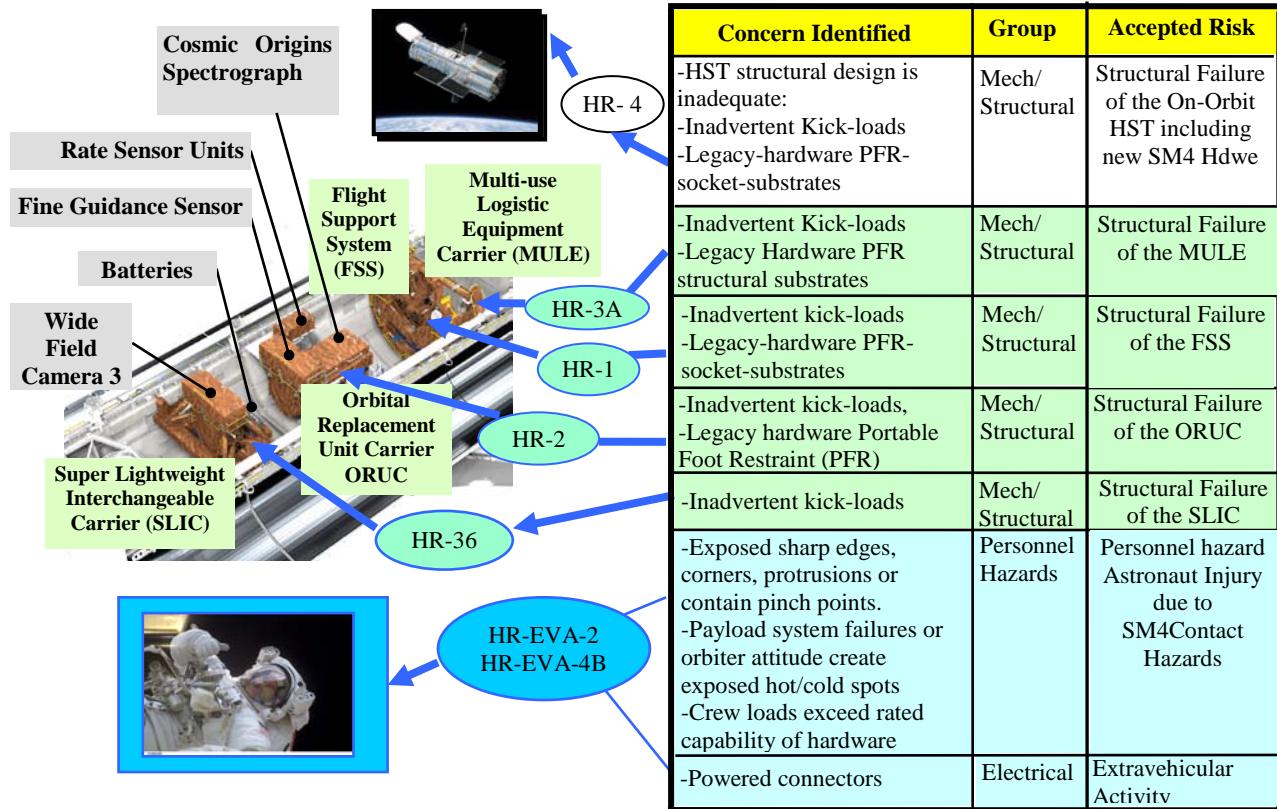


Figure 4. Location of Accepted Risk Hazards within the SM4 Mission Payload

3.1 Accepted Risks-Structural

Of the seven (7) accepted risk hazard reports, five (5) address structural hazards. The structural hazards fall into three (3) major categories:

3.1.1 Kick loads

Not all elements of the carriers, components or HST can meet kick load requirements as defined in JSC Safety Requirements (NSTS 07700, Volume 14, App. 7). An inadvertent kick could result in a Sharp Edge and/or damage rendering the carrier or equipment unsafe for landing. The sensitive IMAX camera assembly which included a glass cover was located along a busy translation path on ORUC in the payload bay between the airlock and telescope, and the Relative Navigation Sensor (RNS) cameras were behind the telescope on the MULE near where hardware was to be collected for installation. In order to mitigate this risk, kick load maps indicating where damage is or is not likely to

occur were developed and provided to the crew. The crew practiced avoiding these locations during training sessions and the locations were provided as a part of on-board documentation used during EVA.

3.1.2 Portable Foot Restraint (PFR) Sockets

All carriers and HST have PFRs installed into substrates on in-bay equipment as well as HST for crew use during EVA. A broken PFR socket could result in sharp edges or damage supporting structure introducing a collision hazard. HST and three (3) of four (4) carriers were developed using different requirements than currently exist for this type of hardware. In order to mitigate this hazard, nominal PFR settings and capabilities were documented in Flight Rules and the JSC EVA Checklist used on-orbit. Following each Neutral Buoyancy Lab (NBL) practice run, EVA team member captured PFR settings and structural engineers analyzed each setting against capabilities. EVA team members then notified the crew as to whether or not the PFR settings were

within substrate capabilities. PFR settings were included as part of the EVA checklist. Additionally, tools were developed permitting PFR substrate structural analysis in real-time, should a different setting be needed on-orbit due to a contingency or last-minute change. PFR settings for a potential servicing mission without the Remote Manipulator System (RMS) or arm were also developed and practiced during NBL training.

3.1.3 RMS Rates and Clearances

As HST is captured and serviced with solar arrays fully deployed and contains vibration-sensitive equipment, the rate of capture and stowage onto the FSS (Flight Support System) must be carefully controlled to avoid damage. All previous servicing missions restricted RMS handling rates for HST informally. Prior to SM4, a specific value was not specified within hazard report documentation. For SM4, the addition of the SCM designed to provide an attachment for a future rendezvous significantly reduced the clearances between the FSS and HST. Concern about the reduced clearance resulted in extensive studies and the addition of scuff plates to the FSS to provide positive motion control. A flight rule was written to formally restrict RMS rates to a maximum of 63% of the value specified in HST's Interface Control Document with the Orbiter. The PDRS (Payload Data Retrieval System) Operations Checklist documented the RMS settings used to configure for the reduced rate.

3.2. Accepted Risks-Electrical

In order to manipulate connectors, inhibits are required to assure that no electricity can flow while the crew is nearby. Should a powered connector result in a bent pin or contain orbital debris, there is risk of molten metal or, depending on the available voltage, shock. The type and placement of at least 2 inhibits is defined by JSC requirements. However, as for previous servicing missions, several connectors could not meet these requirements. (Reference NSTS 1700.7B para. 200.1: JSC MA2-99-170 Crew Mating/Demating of Powered Connectors). Two hazard reports were needed to document the connectors. One report (HR-EVA4A) documented inhibits and controls for connectors that met the requirements. An ARHR was written to document those connectors that could not meet the requirements and required operational controls to mitigate risk. For both reports, schematics and detailed assessments for nominal and off-nominal connectors were analyzed and hazards mitigated.

The highest risk connectors are those that remain powered during their manipulation. For SM4, this occurred during the installation of the two battery modules. Seven powered connector mate/demate

operations were addressed, five of which were Off-Nominal Tasks. Identified with each operation is requirement non-compliance and reason, along with acceptance rationale.

3.3. Accepted Risks-Known Contact Hazards

Four types of contact hazards were addressed: Temperature (high or low), Sharp Edge, Pinch Point and Protrusion. For the temperature related contact hazards, hot or cold temperatures could exceed glove rating and injure crew. Sharp edges can puncture the EMU and/or gloves, causing crew injury and/or reducing available EVA time. Pinch points and protrusions can interfere with the crew's ability to access either HST or needed equipment on the carriers.

3.3.1 Thermal Exceedances

Crew Aids & Tools (CATs) and Handrails can expose personnel to hot/high touch temperatures. Non-compliant CATs were specifically documented as an appendix in the Contact Restrictions Document. The risk to the crew is injury due to excessive exposure to hot or cold temperatures. Handrails are exposed to space and uninsulated. Long duration contact frequently occurs during servicing, especially when supporting installation of a replacement unit or instrument.

Flight Rules were used to define acceptable duration in Sun solar inertial attitude (worst case COLD or HOT) during EVA (e.g., handrails). Where the risk was higher, a warning was included on the EVA checklist as was done for the Wide-Field Camera installation. Additionally, the crew is trained to minimize exposure of CATs to the environment and use glove warmers when necessary or called out as a part of the EVA checklist. Due to sensitive optics, HST required various "sun protect" attitudes, resulting in exposure to very cold attitudes. Operations with instrument changeouts (COS, WFC, FGS) were carefully outlined in the timeline and the crew thoroughly understood the implications of the temperature extremes to their own safety as well in the vacuum of space. As for other operational controls, exposure times were a part of the scripted timeline.

3.3.2 Known Sharp Edges, Pinch Points and Protrusions

In some cases, tools required a functional sharp edge to perform their specified task. The sharp edge could result from small fastener size or a need to cut or puncture to perform the task. On SM4, several tasks were conducted in areas not designed for servicing. These areas, in particular, frequently required very small tools

or cutting devices to access equipment internal to HST. Additionally, pinch points were unavoidable due to the need for hinges or pivot points. Protrusions are sometimes unavoidable due to design.

Each tool and every piece of equipment in the payload bay was inspected for sharp edges and pinch points by members of the HST Safety Team as well as KSC's Safety team. If the sharp edge could not be eliminated or was required for the item to perform its function, the Safety/EVA engineer documents its location for crew awareness and training to mitigate the occurrence of crew contact. The sharp edge or pinch point became listed within the Contact Restrictions Document (CRD) which contains identified contact hazards since the launch of HST. Once a part of the CRD, warnings and cautions were incorporated into other documents to assure that the crew remembered the operational control in real-time. Project safety engineers verified the operational controls had been implemented through reviewing Flight Data Files (FDF) procedures, and EVA Requirement Documents for CAUTION and WARNING notes, safe operation, and to identify requirements for crew related safety verification methods. The EVA Safety process implements these controls into the training requirements.

4. EVA PROCESSES

Developing scripts and timelines for EVA day operations required a coordinated effort including detailed engineering, prototypes, crew trials, re-design, and training. Training activities, coordinated and choreographed by the EVA team, include Neutral Buoyancy Laboratory (NBL) runs, crew briefings, one-gravity trainer sessions, and virtual reality sessions.

These tasks resulted in well-designed and understood EVA tools and clear techniques for conducting the EVA. The safety engineering team supports the design process at their home-base Goddard Space Flight Center (GSFC) and also the astronauts' office at Johnson Space Center (JSC) and during tool and EVA procedure development; while the EVA team assigned a dedicated safety representative to present EVA-specific topics to the JSC PSRP and participate in Hazard Report (HR) reviews. The entire team worked hand-in-hand with the CATs designers and developers through each stage from preliminary design to manufacture and delivery.

Several peer-reviewed documents were established by the EVA team to document operational safety controls. The EVA Requirements Document (SMR-4028), provided baseline procedures and included cautions, warnings, notes, and constraints necessary for the safety of the crew, success of the mission, preservation of HST, and the complex interfaces in between the various elements. The EVA Requirements were then

incorporated into the EVA Checklist, which is the step-by-step procedures used on-orbit by the crew during EVA. Off-nominal situations are addressed in the EVA Contingency Procedures (SMR-4064) and accounted for the severity level and likelihood of potential problems. Using this document, JSC developed a "Workarounds Cribsheet", which provided instruction for anticipated problems which might have occurred during EVA. For example, this document provided the minimum number of turns of locks on in-bay stowage equipment required for safe landing and HST berthing.

The EVA Verification Plan (HST-TR-010303, Appendix D) documented fit checks performed for each tool and interface for both HST and the carriers. Fig. 5 shows a fit check being performed on the Science Instrument Command and Data Handling (SI C&DH) Unit. Verification was provided by reviewing signed-off work orders. The plan identified tool-to-tool fit, with instrument interfaces, translation paths, worksite access, mechanical advantage, and visual cues.



Figure 5. Fit Check on SI C&DH with Power Grip Tool (PGT) and 6" wobble socket extension

The EVA team conducted fit checks on equipment interfaces with the Go/No-Go Gauge, every possible socket option and extension, and tools in line with the Torque Matrix established by GSFC Mechanical Engineering. For example, all corners of the SI C&DH were evaluated for any interferences and assessed tight clearances. At the pad at the Kennedy Space Center (KSC) after hardware was installed on the stowage carriers, the EVA team verified that setup was in safe configuration for the mission within days of launch during the Payload Walk-down for quality control inspection of the equipment.

As discussed in the previous section, the EVA Contact Restrictions Document (HST-OPS-010086) provided a single-point reference for keep out zones, no touch and no damage areas which crewmembers must not enter due to potential sharp edges, pinch points, protrusions, hot surfaces, high voltage, hardware damage by collision, loss of HST capability by electromagnetic fields, contamination by optical scattering via particulates or molecular absorption, reduction of radioactive capability. Examples of documented “No Touch” areas included all cable harnesses and ORU connector sockets, and selected connectors that have power applied to them during changeouts (such as the Battery modules) are listed. These zones were reviewed with the crew at every training session.

During SM4, safety issues were considered, analyzed and addressed in detail during tool design and in detail during crew training. Even before STS-125 crew was named, crew candidates conducted engineering evaluations to understand and address unique hardware design objectives for safety. One example – Alignment guides to prevent damage to carrier bolts were provided to reduce the possibility of incorrect stowage which could have resulted in loose equipment in the payload bay. Once selected, the EVA team presented 1g overviews to the crew at JSC providing early hands-on experience with the hardware before going to NBL. Under water, spacewalks were carefully choreographed in a unique weightless-like environment, including reach and access, visibility, translation paths, and induced loads (see Fig. 6). After hours, days and years of practice, running the tasks in the NBL led to the estimation of time to complete these activities safely and the development of a timeline which balanced efficiency and safe execution.

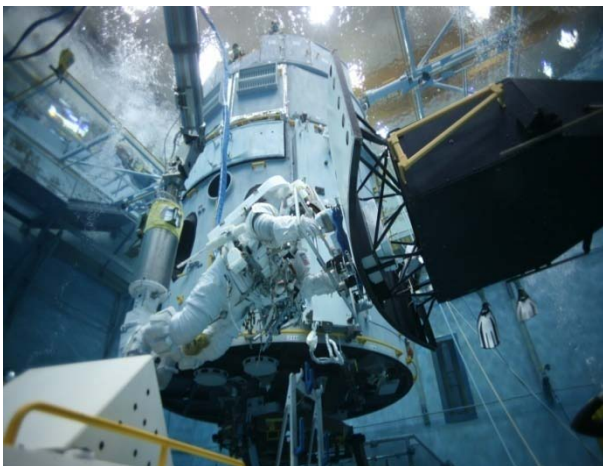


Figure 6. Stowage of WFPC-3 on Aft Fixture at NBL

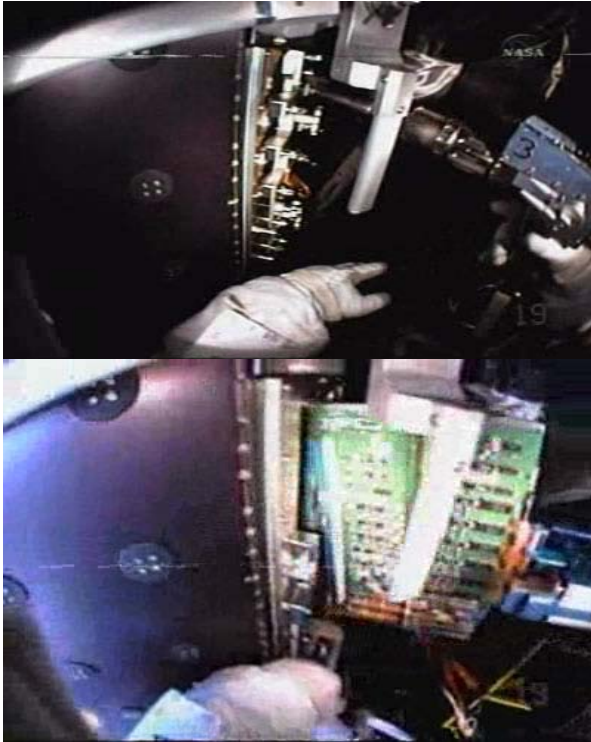
Crew Familiarizations at both GSFC and KSC provided unique opportunities for the crew to interact with hardware designers and experts and practice on actual flight equipment that they would manipulate in space

during the mission. Additionally, flight-like simulators were built for tabletop briefings at JSC along with virtual reality mockups to give the crew the best available sense of what it would be like to handle these new instruments and tools on orbit – including fit, form, and function. Fig. 7 shows the crew practicing SM4 activities with mockup trainer.



Figure 7. STIS Repair 1-G Trainer with Fastener Capture Plate and Mini-Power Tool

During the mission (see Figs. 8 & 9), EVA and Safety personnel supported Mission Control on a 24 hour basis. Even when the crew was sleeping, the ground team was preparing for potential failures – including the possibility that the mission could be cut short and hardware that was not intended to go inside the space shuttle might have to be carried in during an emergency. Safety factors such as material composition and the limitation of airlock dimensions were considered and documented in contingency plans.



*Figure 8. On-Orbit ACS Repair Photos –
Top: Showing PGT engaging Grid Cutter blade
Bottom: Removing ACS Circuit Card, with tool
protecting crew from contact hazards*

5. CONCLUSION

Early attention to safety considerations in mission design and strong verification and validation process for safety requirements helped assure a safe mission. Cooperation between HST's Safety and EVA Teams in implementing and verifying operational controls greatly reduced risk for the crew. Including the crew in developing tools and techniques improved safety and proved invaluable for HST SM4. The close coordination of the mission team through producing and documenting the ARHR's greatly enhanced the understanding of the hazards and controls associated with the mission. Methods used to appropriately mitigate the risk were reviewed not only by HST's Safety and EVA teams members, but also by a panel of experienced engineers at JSC, which provided both insight and oversight for mitigation of hazards on HST SM4. Due to attention to engineering detail and careful planning and cooperation by HST's EVA and Safety teams NASA's Hubble Space Telescope has access to a better view of the universe and seven crew members returned safely home.

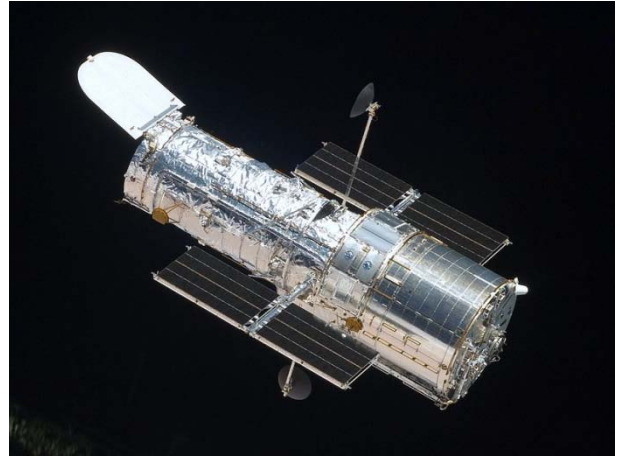


Figure 9. On-Orbit photo: Refurbished Hubble Space Telescope poised for new discoveries



Figure 10. "Weight on Wheels" Payload Flight Safety Phase Completed